ADVANCES IN EROSION PREDICTION OF AXIAL FLOW EXPANDERS

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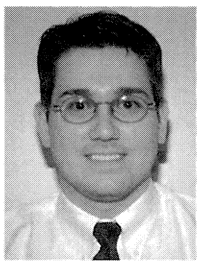

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ABSTRACT

Hot gas expander flow path erosion costs the refining industry millions of dollars per shutdown in labor, materials, and lost production to replace eroded components. With erosion being the life limiting factor, there is great interest in predicting erosion patterns and designing new hardware to extend the operating life of the fluid catalytic cracking (FCC) expander. This paper discusses a method of predicting flow path erosion and deposition using computational fluid dynamics (CFD) coupled with empirical erosion data. Also included are the design criteria established to extend the expander life. Excellent correlation exists between the actual hardware and the CFD predictions. With an understanding of the particle dynamics, new aerodynamically efficient components may be developed to significantly increase the reliability and life of the expander. Using this proven technology, opportunities exist to improve the erosion life of FCC expanders as well as other types of turbomachinery operating in dirty gas environments.

INTRODUCTION

The fluid catalytic cracking (FCC) expander is a critical component in the refining process and is a challenging application of rotating machinery. The FCC expander is a power turbine used to recover available energy from the flue (waste) gas of the refining process (Figure 1). Flue gas conditions at the expander inlet can vary in temperature from 1200°F to 1400°F (650°C to 760°C), pressures of 20 psig to 45 psig (1.4 kg/cm^{2}G to 3.2 kg/cm^{2}G) and flow rates up to 1,400,000 lb/hr (635,000 kg/hr). The flue gas is typically laden with 80 to 120 ppm catalyst particles, which are of an alumina/silica base with fine particles of ceramic known as zeolite.

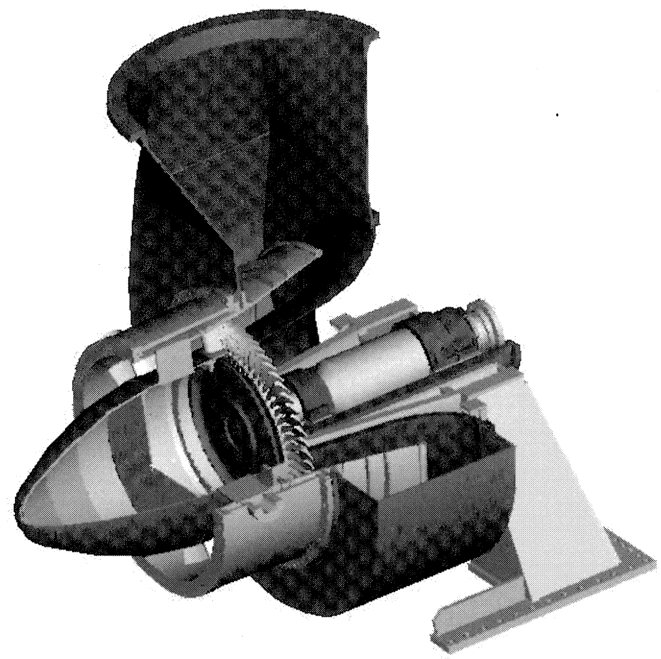

Figure 1. Cutaway of Typical FCC Expander.

The catalyst particles can be more aggressive than aluminum oxide and can cause severe erosion in the expander flow path. The components most effected by erosion are the stator vanes and rotor blades. The catalyst particles also have a tendency to deposit onto flow path components. Deposition is a complex phenomenon involving the thermodynamics and aerodynamics of the flow stream. One distinct characteristic of deposition is the tendency to form in areas of low velocity. The most common and most detrimental area of deposition is on the shroud surface above the rotor blades. As the deposit thickness increases, contact can be made with the rotor blades. Time, temperature, and rubbing action sinters the catalyst and causes blade tip wear and cracking.

Flow path erosion and deposition have dictated the turnaround cycle for some units. In many FCC units, the expander drives the main air blower for the refining process; therefore, the process must shutdown when overhauling the expander. The turnaround cycle for an expander is typically two to four years, while the rest of the FCC unit's equipment requires maintenance every four to six years. Extending the operating cycle of the expander will not only reduce the hardware replacement costs, but also increase the FCC unit's availability. Loss in production of an FCC unit may cost the refinery up to a million dollars per day.

Current expander airfoil designs are generally based on aerodynamic considerations. Using the latest computational fluid dynamics (CFD) codes, a prediction and understanding of the catalyst particle dynamics can be obtained. To support the particle dynamic model, lab testing of various materials and coatings was conducted to enable computer models of erosion to be generated. The empirical data obtained is coupled with the CFD analysis, making this a special application of the technology. This paper is an overview of the tools and techniques used to predict erosion and redesign expander flow path components to reduce the potential for erosion and deposition, in an effort to extend the expander operating life.

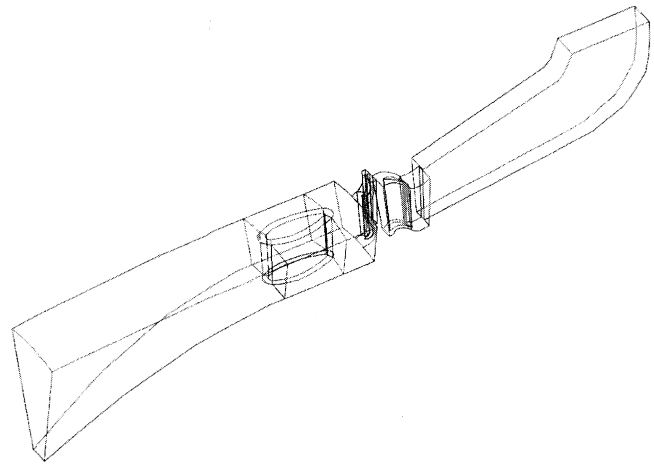

Figure 2. Wireframe Definition of Flow Path Model Used for CFD Analysis.

CFD ANALYSIS

Introduction on the Use of CFD

The use of computational fluid dynamics (CFD) to analyze axial turbomachinery is not new to the industry. However, the application of CFD to predict erosion within FCC expanders is a relatively new technology. It is because CFD codes have improved significantly in computational ability and ease of use that the application of this technology has become possible. This, coupled with the improvement in computer hardware, allows for the prediction of erosion within the highly complex flow field of an FCC expander.

Calculating erosion patterns within an axial expander is a very complex task involving rotating blades, complicated 3D geometry, and high speed compressible flow. A commercially available CFD code commonly used in the turbomachinery industry was used to perform the analysis. This code provides software for generation of the model, solving for the resulting flow field, and post-processing the solution.

Computational Model

To perform a CFD analysis, a mesh must be generated that describes the flow path geometry. This mesh is later used by the code to solve the basic equations of fluid motion (mass, momentum, and energy). A computational mesh is created for each expander flow path geometry analyzed using the appropriate pre-processing software. The entire expander flow path (from nosecone to diffuser exit) is modeled, as shown in Figure 2, and used to solve the problem. Since the flow field is assumed to be periodic, only one passage is analyzed within the stator and rotor blades along with a narrow segment upstream and downstream of the blading. This assumption substantially reduces the mesh size and solution time of the problem. Due to the complexity of the stator and rotor blading geometry, a mesh for the four major segments of the flow path (nosecone/strut, stator, rotor, exit diffuser) is created independently and later "joined" together to create the final computational mesh. The resulting mesh consists of approximately 250,000 nodes. Figure 3 shows the resulting rotor and stator surface mesh. This multiblock structured grid simplifies mesh construction and later geometric modifications.

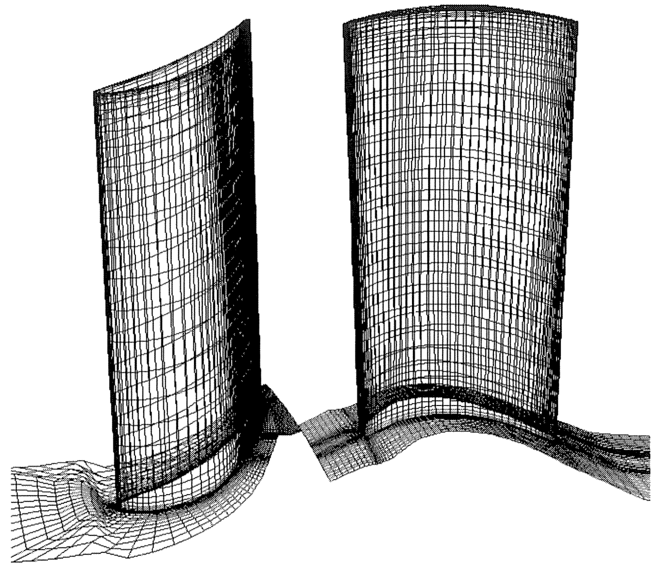

Figure 3. Illustration of Rotor and Stator Surface Mesh.

The FCC expander flow paths are analyzed using a CFD code that allows for the solution of 3D, turbulent, high speed compressible flows in multiple reference frames, as are typically found within axial expanders. Because of the rotating blade row within the expander, the rotor mesh is solved in the rotating reference frame, with the balance solved in the stationary frame. The software handles the transfer of information between the stationary and rotating reference frame based upon specified interface attachments. Turbulent fluctuations are accounted for using the k-epsilon turbulence model with wall functions. Particle tracking capabilities allow for the flow field solution to be affected by the particle paths. In this type of analysis, the particle trajectory through the expander and the calculated particle momentum influence the flow field solution. The necessity of this type of analysis is dependent upon the amount of catalyst passing through the actual unit. To account for this momentum exchange, several thousand particles are injected during the solution process. After the flow field solution is obtained, several hundred thousand particles are uniformly injected at the domain inlet and tracked (via Lagrangian particle tracking model) through the entire flow path. Several different particle sizes (ranging from 1 μm to 50 μm) are injected, based upon the known particle distribution of the expander being analyzed. In addition to the standard fluid dynamic variables, the particle impact velocity and impact angle (relative to the surface normal) are recorded at all wall boundaries, and used to calculate erosion rate and rebound characteristics using a proprietary empirical model. Inlet total pressure, total temperature, and turbulence properties are specified at the inlet boundary, and static pressure is specified at the exit boundary to constrain the problem. Mass flow is calculated from these boundary conditions. Solution time (including erosion analysis) is approximately 15 hours on a UNIX workstation with a Riscl0000 processor operating at 195 MHz with 512 MB of RAM.

Erosion Model

During the process of obtaining the CFD results, particle trajectories are calculated; therefore, information about how the particle erodes and rebounds from the surface is required. This information is obtained from empirical relationships developed using a high temperature erosion test rig (Tabakoff, 1988). The test rig is composed of a compressor and gas turbine combustor, which is used to reproduce the gas velocities and temperatures experienced by the expander blading. Catalyst particles are injected into the hot rig and are accelerated to the velocities and impact angles experienced in the expander. Utilizing laser Doppler velocimetry, the catalyst particle rebound characteristics and erosion rates are measured for various expander blade materials and coatings. It has been found that erosion rate is highly dependent upon particle characteristics, particle impact velocity, impingement angle (relative to the surface normal), temperature, and material. Typical test results are shown in Figure 4. Empirical correlations were developed from the test results and are incorporated into the CFD analysis.

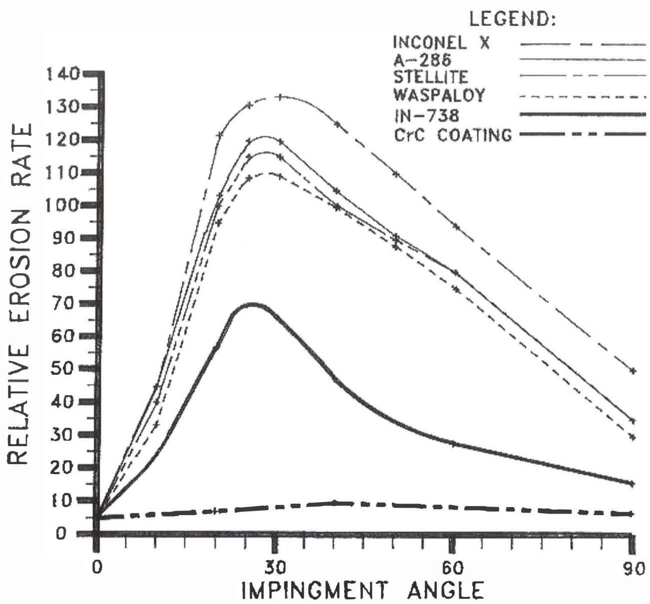

Figure 4. Relative Erosion Rates for Various Materials.

COMPARISON OF CFD PREDICTION TO ACTIVE UNITS

Particle erosion of the expander flow path components can be classified into two major categories: primary and secondary erosion. Primary erosion is generally caused by the larger (>5 µm) catalyst particles and occurs on the pressure surface of the airfoil or the leading edge of the airfoil. Secondary erosion occurs when smaller catalyst particles get caught in areas of the flow path where secondary flows exist. Figure 5 illustrates typical erosion patterns. For a number of units, the rotor blades experience secondary erosion at the hub of the rotor blade. Changes to the aerodynamics can be incorporated into the flow path design to eliminate this phenomenon.

Field experience has been used as a calibration tool for the CFD models. Retired hardware and online blade photographs have been compared with the CFD predicted erosion patterns. Figure 6 illustrates an example of rotor blade predicted erosion versus the actual blade. The oval erosion pattern covers the mid two-thirds of the span in the midchord region of the airfoil. This pattern is an example of primary erosion and is typical in the FCC application. Figure 7 provides a comparison of the stator vane erosion seen in service and the CFD predicted pattern. The stator vane has severe erosion of the leading edge and the airfoil to the extent of complete material loss. Wear of this magnitude not only reduces the aerodynamic efficiency of the unit, but also causes excessive erosion on the rotor blade leading edge. In most analyses, excellent correlation exists between actual hardware erosion and the CFD predicted erosion patterns.

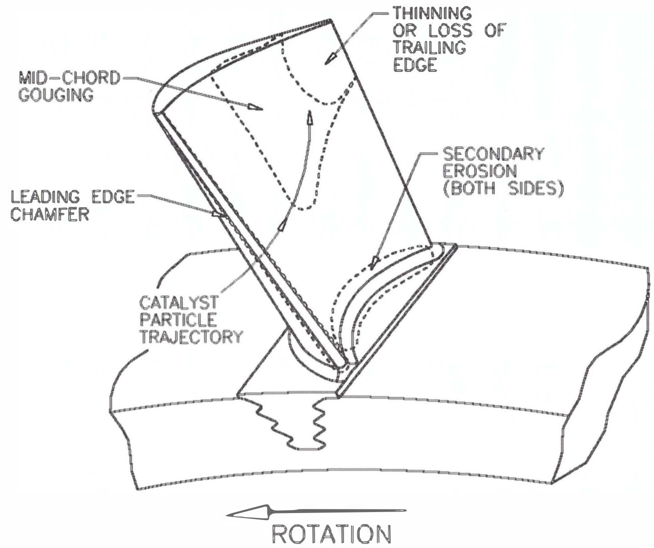

Figure 5. Typical Erosion Patterns.

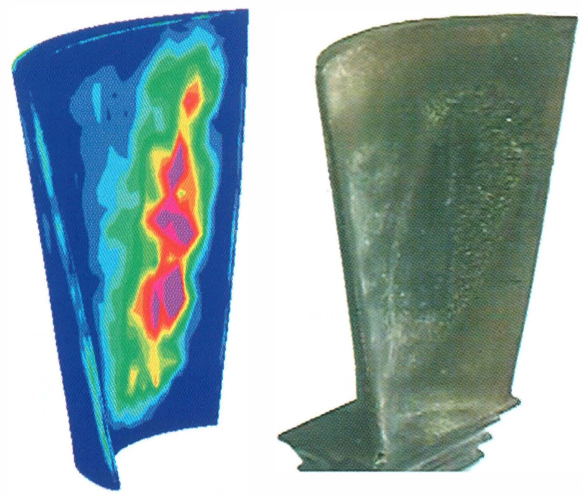

Figure 6. Comparison of Predicted and Actual Rotor Erosion.

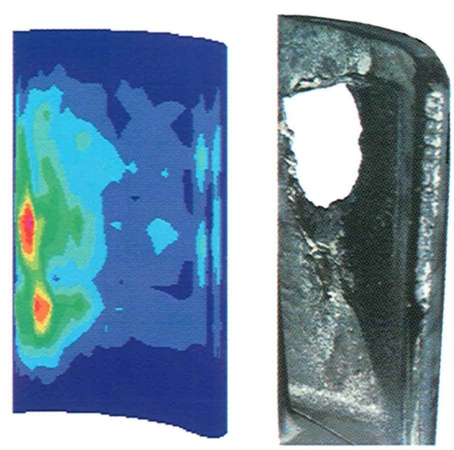

Figure 7. Comparison of Predicted and Actual Stator Erosion.

Although deposition cannot be readily modeled, various flow path designs have been modeled, classified, and compared with field experiences. It has been determined that certain flow path angles are more susceptible to shroud deposition. Using CFD, different shroud designs have been analyzed. Figure 8 compares the particle traces at two different shroud angles above the rotor blades. The boundary layer effects are generally stronger with steeper flow paths, and have been shown to increase the amount of deposition.

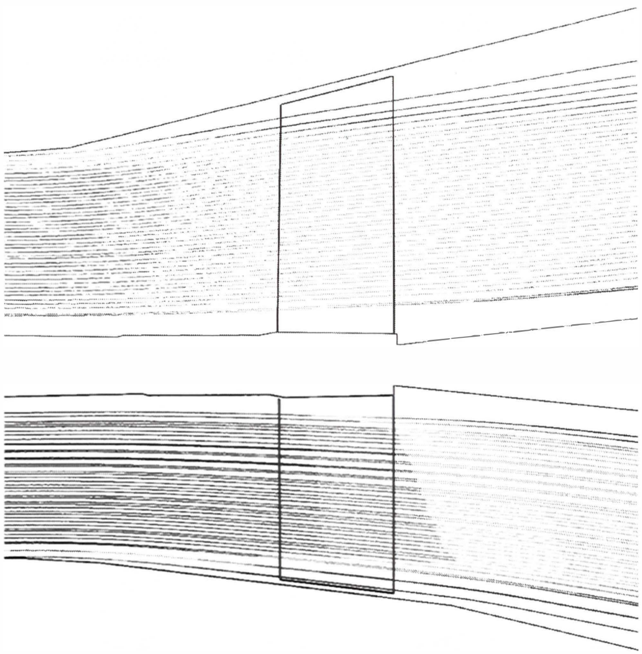

Figure 8. Particle Traces at Two Shroud Angles (Rotor Blade Shown).

GUIDELINES FOR REDUCING EROSION

The techniques used to design expander airfoils and flow paths were developed in the 1960s using basic aerodynamic principles and inviscid flow computations. With the advent of today's CFD codes, viscous flow calculations and particle tracking capabilities allow for a better understanding of the particle dynamics within the expander flow path. This, coupled with aerodynamic considerations, yields several design guidelines for reducing the erosive effects of abrasive particles.

Create Uniform Particle Distributions

A concentrated impact of erosive particles will lead to accelerated localized erosion. If the number of particles cannot be reduced in these local regions, then uniformly distributing the particles within the flow path annulus will promote a more uniform wear pattern and avoid localized erosion. In addition to the airfoil designs, several components within an FCC expander influence particle distribution including the nosecone, nosecone struts, shroud, and exhaust diffuser. The nosecone helps to accelerate and distribute the gas uniformly to the stator row and its shape/profile influences the rate of acceleration. As seen in Figure 9, blunt nosecones with tight curvatures and high rates of acceleration tend to concentrate particles toward the midspan of the flow path. The tendency to concentrate catalyst particles also occurs due to steps or discontinuities on the outer wall or shroud. Smooth profile transitions on the nosecone and the outer wall help to maintain a more uniform particle distribution.

The number and profile shape of the nosecone struts also influence the particle distribution. Wakes created by poorly designed struts create a "shadow" on the downstream stators behind the struts, diverting the particles to adjoining stators and increasing particle concentration. Nosecone struts should be designed with a profile shape that minimizes the wake downstream, and positioned far enough upstream to allow for a uniform particle distribution into the stators.

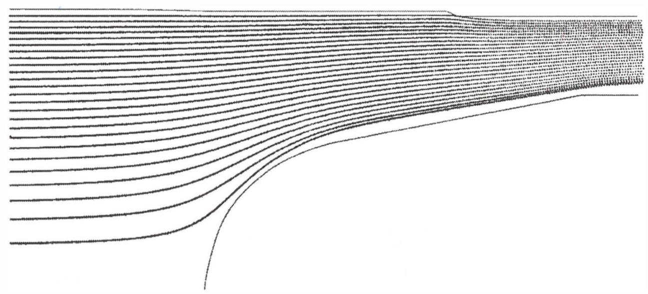

Figure 9. Particle Traces for a Poor Nosecone Design.

Reduce Surface/Particle Impact Velocities

Since surface erosion is strongly dependent on particle impact velocity, reducing these velocities will lead to a reduction in erosion. The velocity at which a particle impacts a surface depends upon a number of factors including particle size, density, and gas velocity. Smaller particles are more likely to follow the gas flow path than larger particles, since they have less inertia and drag. They also more closely approach the gas velocity. Generally, if gas velocities can be reduced, particle velocities also drop, which tends to reduce erosion.

Gas velocities are mainly influenced by flow area, rotational speed (which is normally fixed), and airfoil shape for a given pressure ratio. The highest velocities within an expander tend to be in the throat region of the stator with velocities approaching sonic. Rotor throat velocities can also be high (in the relative frame), if the stage reaction is high. Reducing the stator velocities by increasing the throat area will not only reduce erosion on the stator, but also reduce velocities into the downstream rotor blade row. Airfoil shape influences the surface velocities around the airfoil, and should be designed to minimize velocities and eliminate regions of high acceleration and deceleration. Figure 10 shows an example of high localized velocity on the suction surface near the leading edge caused by the rotor airfoil shape. High localized velocities are sometimes a function of leading edge shape and vary with the flow incidence (the difference between flow angle and blade metal angle). Surface velocities can also be affected by changing the amount of turning done by the airfoil and selecting appropriate aspect ratios (blade span/axial chord). Any region of high velocity within the flow path has the potential to be a contributor to erosion. A good erosion proof airfoil design needs to consider all the above-mentioned parameters. Although these changes may reduce erosion, the designer must be cognizant of the aerodynamic effects, such as changes in blade aerodynamic and structural loadings, torque, reaction, efficiency, and mass flow that may be created by these modifications.

Eliminate Low Velocity and Separated Flow Regions

Flow separation, where a localized region of recirculation or low velocity is created, can be detrimental due to entrapment of particles in the recirculation region. The particles tend to grind at the surface, leading to localized erosion. Flow separation can be caused by abrupt changes in the flow path geometry and by high incidence at the airfoil leading edges. Figure 11 shows an example of recirculation due to high incidence. Note the low velocity within the circulation region, as well as a high localized velocity in the flow stream at the leading edge.

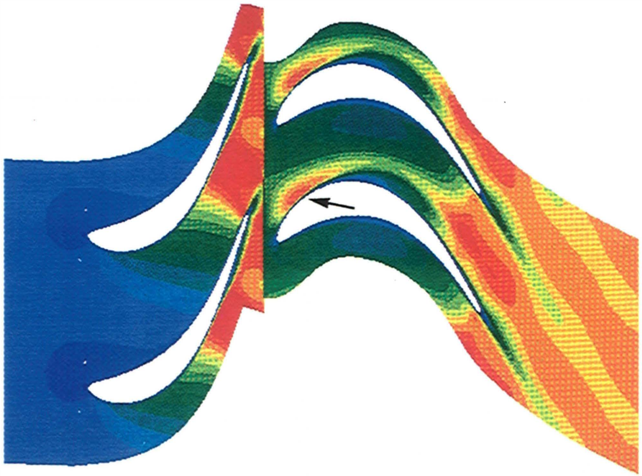

Figure 10. Rotor Relative Mach Number Distribution Showing Localized Acceleration.

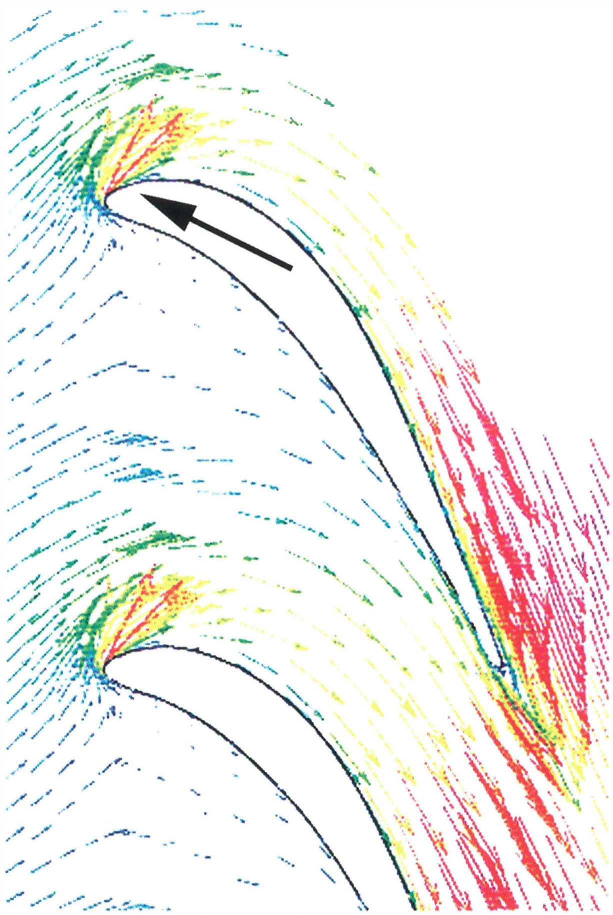

Figure 11. Rotor Velocity Vectors Showing Separated Flow.

Although CFD cannot currently predict catalyst deposition, field experience indicates that deposition can occur in areas of low velocity, such as separated flow regions. One region where deposition has historically occurred is on the shroud above the rotor blades. Many shroud designs have very steep flow path angles, which potentially lead to flow separation. Redesigning the shroud to prevent flow separation reduces the likelihood of catalyst deposition. Designing to eliminate flow separation can reduce both the erosion and deposition potential of the expander.

Improve Work Distribution Over Blade Span

Optimizing the stage work distribution from hub to shroud will not only improve aerodynamic efficiency, but also reduce the potential for secondary erosion. Secondary erosion, which mainly occurs near or on the hub surface of the rotor blades, is strongly influenced by secondary flows. Figure 12 shows secondary flow on a rotor blade and how the gas velocities deviate from those of the main flow stream. Secondary flows that lead to erosion are mainly surface boundary layer effects and are driven by pressure distributions near the surface. Low hub reaction, which is common in traditional stage designs, creates unfavorable pressure gradients that strengthen secondary flows and, as a result, secondary erosion. A more uniform reaction (or work distribution) from hub to shroud is the most favorable situation and can be accomplished by careful design of the stator and rotor blading.

Figure 12. Secondary Flow Patterns on the Pressure Surface of a Rotor Blade.

Secondary flow can also be influenced by expander cooling steam injection that mixes with the main flow stream near the base of the blading. These flows can aggravate secondary erosion caused by low hub reactions and/or create secondary erosion from turbulent mixing of the two flowstreams.

REDESIGNED FLOW PATHS USING CFD

Optimized Using Current Technology

In 1994, the first expander was modeled and optimized using CFD and particle tracking. Prior to this optimization, the subject expander's longest operating campaign was only 22 months and significant erosion damage had been present. To optimize the design, the stators were modeled at various settings (stagger angles) to determine the minimum amount of flow path erosion. Figure 13 compares the rotor blade erosion at two stator vane settings. Additionally, the nosecone profile was optimized to improve catalyst distribution. After completing a successful four year run following the optimization, the subject expander's rotor blades show little to no erosion. Figure 14 shows the predicted erosion pattern and the actual blade after four years of operation. Note that no primary or secondary erosion can be seen on the rotor blade. Although the CFD prediction highlights an erosion pattern, the sacrificial coating was not breached, therefore no signs of erosion are evident. This optimization resulted in a 100 percent plus increase in expander service life.

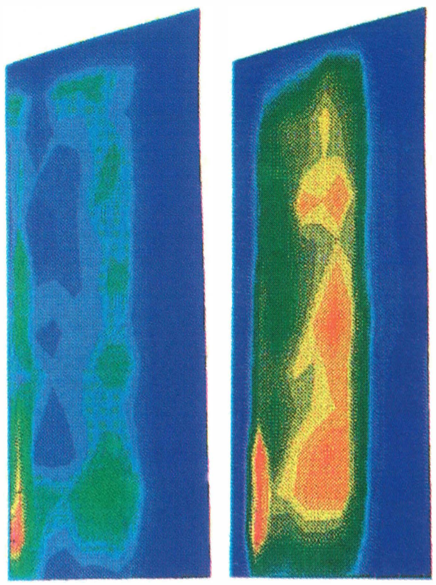

Figure 13. Comparison of Rotor Erosion for Two Different Stator Settings.

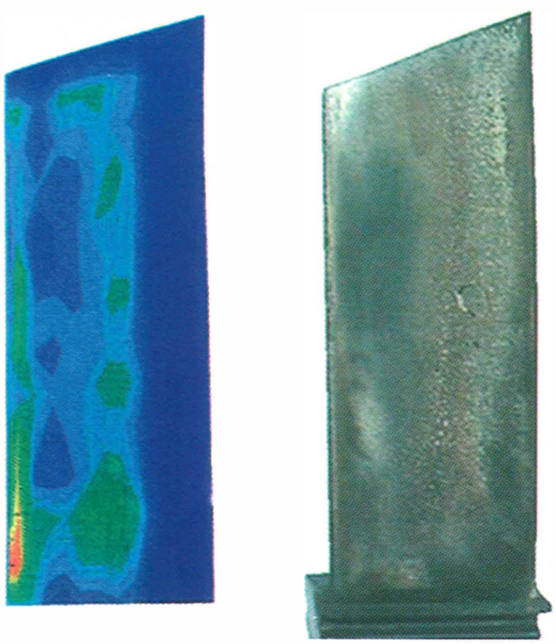

Figure 14. Comparison of Predicted and Actual Rotor Erosion After Four Years.

Several other expanders have been optimized based upon the finding in CFD analyses. The following example is a unit experiencing severe secondary erosion. The expander flow path utilizes a fairly short rotor blade that is inherently conducive to low hub reaction. The subject unit was limited to a two year operating campaign between overhauls due to severe secondary erosion. Figure 15 illustrates the secondary erosion at the base of the blade. The flow path has been redesigned to increase the hub reaction and has been in service since July 1998.

Figure 15. Example of Actual Secondary Erosion.

New Airfoil Designs

The next step of the redesign process includes the review of new airfoil shapes for the FCC expander application. Airfoils used in the expander were developed as early as 1961, and were defined using aerodynamic principles without considering the effects of catalyst erosion. New airfoil designs, specifically rotor blades, have been developed for this application up to the early 1980s using the same principles. With the aid of CFD, designs can be modified to include the particle dynamic effects. For example, a compound lean stator design was modeled with an existing rotor blade to determine its effects. The compound lean stator concept has been applied to industrial gas turbines to improve the work load distribution and blading efficiency. Figure 16 compares the existing stator and rotor blade erosion with the compound lean stator and existing rotor blade design. This is an example of how improving the work distribution for aerodynamic performance reduces the particle dynamic effects and subsequently reduces the erosion rate. For this particular analysis, the predicted erosion was reduced by approximately one order of magnitude.

CONCLUSIONS

With the latest CFD tools, laboratory testing, and field experience, erosion patterns can be predicted in axial expanders. Excellent qualitative agreement exists between the analytical studies and the actual hardware. To date, the expander service life has been increased 50 to 100 percent using CFD. Utilizing the tools and the design criteria highlighted in this paper, new airfoil shapes can be designed to optimize erosion life and aerodynamic performance. The next evolution in this type of modeling is to include the effects of erosion resistant coatings on the airfoils and, with particle loading information from the field, predict remaining blade life during the unit's operating campaign. Although this paper is dedicated to the FCC expander, the models can be used to predict erosion in other types of turbomachinery and vessels operating in dirty gas environments.

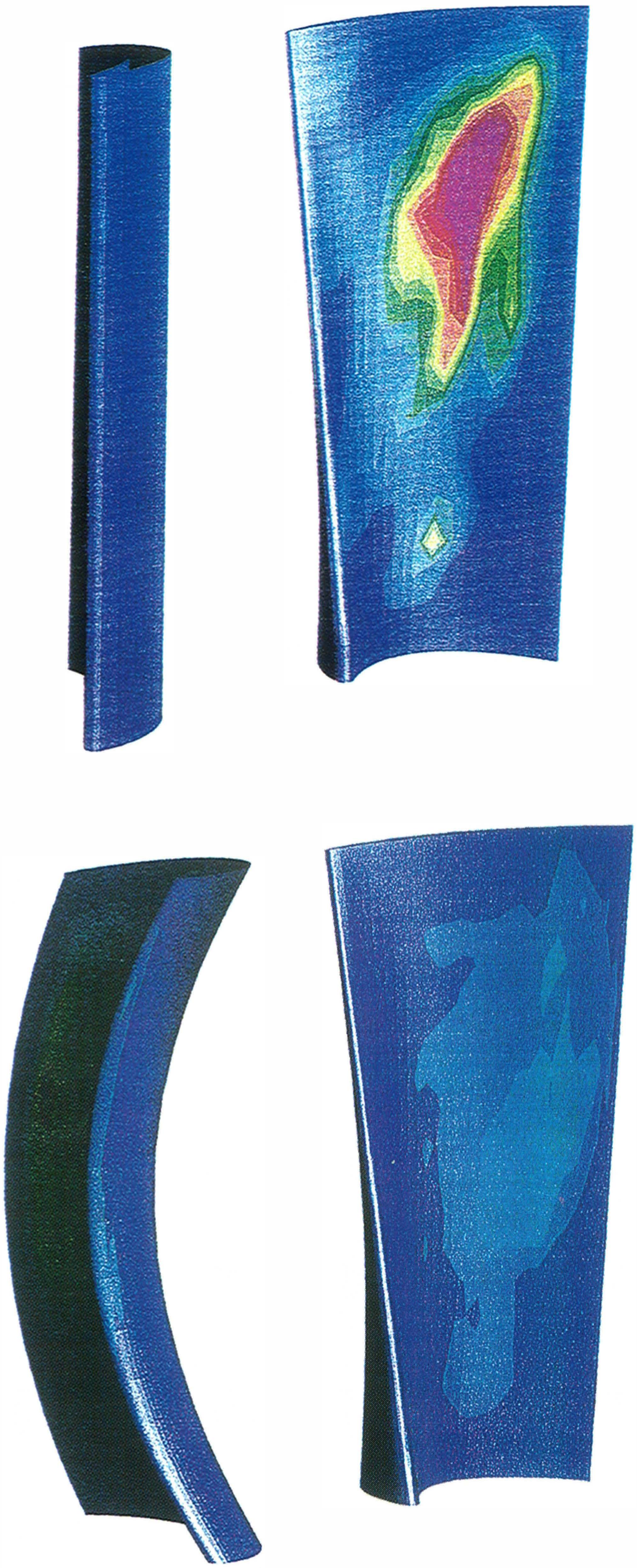

Figure 16. Effect of Compound Lean Stator on Rotor Erosion.

REFERENCES

Tabakoff, W., 1988, "Turbomachinery Alloys Affected by Solid Particles," ASME Paper 88-GT-295.

BIBLIOGRAPHY

"CFX-TASCflow User Documentation," 1998, AEA Technology Engineering Software Ltd.

"CONMEC Expander Roundtable," 1998, CONMEC, Inc.

Linden, D. H., 1994, "Photographic Techniques for Monitoring Turbo Expanders," Second Annual Expander User's Conference, Houston, Texas.

Linden, D. H. and Mindock, M. A., 1995, "Update 1995—Expander Blade Erosion Prediction," Third Annual Expander User's Conference, Houston, Texas.

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